(Fundamental) Particle Physics

Fundamental particles and interactions (inventory & classification, elementarity)

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Dimensional Analysis

Caution !!!

- Hydrogen atom

$$[E_H] = \frac{M\,L^2}{T^2} = [(m_e)^x][(Ze^2)^y][\hbar^z] = M^x\left(\frac{M\,L^3}{T^2}\right)^y\left(\frac{M\,L^2}{T}\right)^z$$

$$\left.\begin{aligned} x + \ \ y + \ \ z &= 1, \\ 3y + 2z &= 2, \\ 2y + \ \ z &= 2, \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} x &= 1, \\ y &= 2, \\ z &= -2, \end{aligned}\right.$$

$$E_H \propto \frac{m_e\,(Ze^2)^2}{(4\pi\epsilon_0)^2\hbar^2},$$

But, that clearly is not all of it!

Dimensional Analysis

Caution !!!

- The true formula *must* depend on c:

$$E_n = -2\alpha^2 \left(m_e c^2\right) \frac{Z^2}{(2n)^2}, \qquad \alpha := \frac{e^2}{(4\pi\epsilon_0)\hbar c} \approx \frac{1}{137.036}.$$

dimension-less parameter and function

$$E_n \propto f(\alpha; n) \left(m_e c^2\right),$$

Characteristic energy

Fundamental Distance

- De Broigli wave-length:

$$\lambda_s = \frac{2\pi\hbar}{p_s} = \frac{2\pi\hbar}{\sqrt{2m_s E_s}}, \qquad i.e., \qquad = \frac{2\pi\hbar c}{E_s},$$

non-relativsitic *relativsitic*

- Event horizon:

escape velocity

$$r_s = \frac{2\,G_N\,m_{m+s}}{c^2}, \qquad \Longleftrightarrow \qquad v_1 = \sqrt{\frac{2G_N\,m_{m+s}}{r_s}} = c,$$

$$r_S \sim \lambda_s \quad \Rightarrow \quad \frac{2\,G_N\,(m_m c^2 + E_s)}{c^4} \sim \frac{2\pi\hbar c}{E_s}$$

Willy-nilly, things are unobservable within r_S $\Rightarrow$ $E_s \sim \sqrt{\pi}\, m_P\, c^2,$

Fundamental Distance

Name	Expression	SI Equivalent	***Part.Phys.*** Equivalent
Length	$\ell_P = \sqrt{\frac{\hbar G_N}{c^3}}$	$1.616\,25 \times 10^{-35}$ m	
Mass	$m_P = \sqrt{\frac{\hbar c}{G_N}}$	$2.176\,44 \times 10^{-8}$ kg	$1.220\,86 \times 10^{19}$ GeV/c^2
Time	$t_P = \sqrt{\frac{\hbar G_N}{c^5}}$	$5.391\,24 \times 10^{-44}$ s	
El. Charge*	$q_P = \sqrt{4\pi\epsilon_0 \hbar c}$	$1.875\,55 \times 10^{-18}$ C	$e/\sqrt{\alpha_e} \approx 11.706\,2\,e$
Temperature	$T_P = \frac{1}{k_B} m_P c^2$	$1.416\,79 \times 10^{32}$ K	

*$\alpha_e \approx 1/137.035\,999\,679$ for low-energy scattering, but grows a little to about $1/126$ near ~ 100 GeV energies.

Quantity	Particle Physics	SI Equivalent
Energy	x MeV	$= x \times 1.602\,18 \times 10^{-13}$ J
Mass	x MeV/c^2	$= x \times 1.782\,66 \times 10^{-30}$ kg
Length	$x\,\hbar c$/MeV	$= x \times 1.973\,27 \times 10^{-13}$ m
Time	$x\,\hbar$/MeV	$= x \times 6.582\,12 \times 10^{-22}$ s

Historical Inventory & Lessons

- Production
  - Cosmic rays: the spectrum includes ***very*** high-energy particles, but is completely uncontrollable
  - Radioactive materials: α,- β- and γ-particles, neutrons… irradiated (by, say, synchrotron radiation) materials…
  - Particle accelerators (& targets), beam-to-beam colliders accelerate by means of electric and magnetic fields
- Detection
  - Geiger, scintillation and Cherenkov counters
  - Cloud,- bubble,- spark,- proportional chambers
  - photographic emulsion

Linked by coincidence triggers

Historical Inventory & Lessons

… a socio-political digression

- Experimental Predispositions
  - In 1909 a table-top experiment discovered the nucleus
  - One could "play around" and …
  - … be surprised.
  - In the latter half of the 20th century…
  - … a G$-worth hole in the ground was filled back (more$)
  - CERN is a multi-national/political/budget/ … facility
  - The US DoE (funds e.g. Fermilab) has –18.9% budget…
  - …you may need to learn Mandarin.

Had a certain gentleman of means not had the penchant for prodding cut-off frog legs with wires…

Historical Inventory & Lessons

… a socio-political digression

- Experimental Predispositions
  - Nowadays, high-energy/elementary particle experiments
  - are carefully orchestrated multi-national/political/budget endeavors, planned and executed on 5–15^{+}-year scales
  - willy-nilly test *known* theory, and are limited thereby
  - No more "unbridled"/accidental experimenting…
  - While theory develops (*tempus fugit*) by leaps and bounds
  - Need an experimental paradigm radically different from
    - smashing experiments (*à la* Rutherford)
    - waiting experiments (proton decay)

Elementarity

… the modern version of Democritus' idea

- Fundamental interactions
  - Electromagnetic interaction (Maxwel equations)
  - Strong nuclear interaction
    - ~1930: *something* like that *must* exist
    - after 1970–'80: QCD
  - Weak nuclear interaction
    - before 1970–'80: Fermi's β-decay and …
    - after 1970–'80: weak (now electro-weak) interaction
  - Gravitation
- Are all gauge (German: *eichen*) interactions

Elementarity

…the fusion of particles and their interactions

- Nuclei and electrons interact *via* Coulomb's field
- Coulomb's field adapts to nuclear and electron motion at the speed of light
  - Nuclei and electrons are *imagined* as particles
  - Electromagnetic field — as a continuum
- And *changes* in the electromagnetic field?
  - Field quantization = quantization of *changes* in the field
  - The field itself is continuous, in which changes are:
    - particles, if localized in position space
    - waves, if localized in momentum space

Elementarity

… the fusion of particles and their interactions

- Coulomb's field is a (background) continuum
- Quanta of the change in Coulomb's field are particles
- Background continuum of Coulomb's field may be viewed as a (Bose-)condensate of photons
- Besides:
  - In the EoM of the field, p^+- and e^--currents = "source"
  - In the EoM of p^+ and e^-, the field provides nonlinearity

$$\partial_\mu F^{\mu\nu} = \underbrace{\frac{q_\Psi}{4\pi\epsilon_0}\overline{\Psi}\boldsymbol{\gamma}^\nu\Psi,}_{\text{4-current}} \qquad \left[i\hbar c\,\boldsymbol{\gamma}^\mu\partial_\mu - mc^2\mathbb{1}\right]\Psi = \underbrace{q_\Psi A_\mu \boldsymbol{\gamma}^\mu \Psi.}_{\text{interaction}}$$

Historical Inventory & Lessons

… a telegraphic review

- J.J. Thomson (1897): cathode rays thru crossed EM field so there is no deflection.
  - ⇛ both speed and the charge/mass ratio
  - ⇛ "constituents" of cathode rays, e^{-}, have a *teeeeeeeensy* mass
  - ⇛ atom consists of electrons inside a positive lump
- E. Rutherford (*JJT's student*, 1909, H. Geiger & E. Marsden): α-rays on gold foil; the atom's positive charge is concentrated in a nucleus ~10,000 × smaller than the atom.
  Named the proton and created the planetary model.
- ⇛ N. Bohr (*ER's postdoc*, 1913): *ad hoc* quantum model:
  - Angular momentum H-atoma = (integer) × $\hbar$.

Why? B/c that's what "works."

Historical Inventory & Lessons

… a telegraphic review

- J. Chadwick (*ER & HG's student*,1928–32): experimental detection of the neutron and named it.
- $\leq$ 1932: only e^-, p^+ and n^0.
- Photon:
  - M. Planck (1900): quantum *emission* of radiation
  - A. Einstein (1905): EM radiation quanta = photons
  - A.H. Compton (1923): $\Delta\lambda = \lambda_C(1-\cos\theta)$, $\lambda_C = h/mc$
  - G. Lewis (1926): name "photon"
  - Coulomb's field = "sea" of photons (condensate, *i.e.* a *collective* of photons behaving as one)

Historical Inventory & Lessons

… a telegraphic review

- Until 1924 (de Broiglie) – 1926 (Schrödinger),
  - the photon *particle* implied that EM radiation is not a *wave*
  - classical interaction: each charged particle has a field, which *instantaneously* creates a force on the other particle
  - interaction ***mediated*** by photons:
    - one particle emits a photon
    - the photon travels
    - the other particle absorbs the photon

Nothing here is ***instantenous***, nor ***omnipresent***!

- 1932, W. Heisenberg: *isospin* (& E. Wigner, 1937)
- 1934, H. Yukawa: strong interaction mediators

Historical Inventory & Lessons

… a telegraphic review

- 1934, H. Yukawa: strong interaction has ~10^{-15} m range

$$V(r) = -g^2 \frac{e^{-r/r_y}}{r}$$

$$m_\pi \sim \frac{\hbar}{r_y c}, \qquad \text{so that} \qquad m_\pi \sim 150\text{–}200\,\text{MeV}/c^2,$$

- 1937 (C.D. Andersen & S.H. Neddermeyer, *East*
  J.C. Street and E.C. Stevenson, *West*): *mesons*
- 1946, Italy: these do not interact strongly, ~106 MeV/c^2
- 1947, R. Marshak & H. Bethe proposed,
  C. Powell (w/C.M.G. Lattes, H. Muirhead and G.P. Ochialini)
  μ (~106 MeV/c^2) & π (~135 & 140 MeV/c^2)

Historical Inventory & Lessons

... a telegraphic review

- Anti-particles
  - Dirac equation: 1st order in space & time
    - Solutions with both $E > 0$ and $E < 0$.
    - States with $E < E_D$ are filled (Pauli's principle!) = "sea"
  - "hole" in the sea = antiparticle
    - A hole in the e^- sea ≠ p^+ (E. Wigner: $e^+ \sim e^-$)
    - Stückleberg-Feynman: e^+ = (e^-, backwards in time)
  - 1931 (C. Anderson): e^+ is experimentally verified.
  - Same theory (Dirac equation) then implies an anti-particle for ***every*** spin-½ fermion.

Historical Inventory & Lessons

… a telegraphic review

- Crossing symmetry
  - If the $A + B \to C + D$ reaction exists, so do
  - $A \to \bar{B} + C + D$,
  - $A + \bar{C} \to \bar{B} + D$,
  - $\bar{C} + \bar{D} \to \bar{A} + \bar{B}$, *etc.*
  - For example:
    - $\gamma + e^- \to \gamma + e^- \;\Rrightarrow\; \gamma + e^+ \to \gamma + e^+$
- Principle of detailed balance (~ reversing time)
  - $A + B \to C + D \;\Rrightarrow\; C + D \to A + B$
- These principles permit new processes ***dinamically***, even if they are ***kinematically*** forbidden.

Compare !!

Historical Inventory & Lessons

… a telegraphic review

- Neutrini
  - β-decay: $A \to B + e^{-}$.
  - $E_e = (m_A{}^2 - m_B{}^2 + m_e{}^2)\, c^2/(2m_A)$
  - In experiments, this is $\max(E_e)$, and E_e varies.
    - N. Bohr: maybe energy conservation fails?
    - W. Pauli: No, but there is a third, invisible particle
      - the “neutron” name was taken by Chadwick
      - so E. Fermi named it: “neutrino”
  - $\pi^{-} \to \mu^{-} + \bar{\nu}_\mu,\ \ \mu^{-} \to \nu_\mu + e^{-} + \bar{\nu}_e$.
    In Powel’s photographs,
    - μ^{-} veers 90° from π^{-}; & e^{-} 90° from μ^{-},
    - E_μ is fixed in the 1st decay, E_e varies in the 2nd one.

Lesson: trust conservation laws!

Historical Inventory & Lessons

… a telegraphic review

- Cowan & Raines (1950's) sought inverse β-decay, $\bar{\nu}_e + p^+ \to n^0 + e^+$ in a giant water tank.
- Very small effect, so they developed the methodology to identify the resulting positron.
- Davis & Harmer: is neutrino = anti-neutrino?
  - No: $\nu_e + n^0 \to p^+ + e^-$ happens, $\bar{\nu}_e + n^0 \to p^+ + e^-$ doesn't.
- 1953 (Konopinski i Mahmoud): preserved ***lepton number***.
- By 1962:
  - leptons (don't interact strongly)
  - hadrons (do interact strongly).

Historical Inventory & Lessons

... a telegraphic review

- Strange particles
  - $K^{\pm}, K^0, \bar{K}^0$ (494 i 498 MeV/c^2)
- Butler, 1947: $K^0 \rightarrow \pi^- + \pi^+$.
- Powel, 1949: $K^+ \rightarrow \pi^- + \pi^+ + \pi^+$.
- Anderson, 1950: $\Lambda^0 \rightarrow p^+ + \pi^-$.
- Why does $p^+ \rightarrow e^+ + \bar{\nu}_e$ not happen?
  - Preserved ***barion*** number (Stückelberg 1938.);
  - ***Strangenes*** number (Gell-Mann, 1965.):
    - preserved in creation (strong int.),
    - violated in decays (weak int.).

Historical Inventory & Lessons

… a telegraphic review

- Eightfold way
- A puzzle of particles of like masses, plotted by charges:
  - electric
  - strange
- Prediction: Ω^- barion (Gell-Mann, early 1960's)
  - 1964: experimental confirmation ☟ prediction betting avg.
  - by ~1963: puzzle is very arbitrary (~7/26)
  - Final form, using $SU(3)$ symmetry & quarks
  - For example, no (*sss*) bound state within the p^+ *octet*, but yes in the *decuplet*

Historical Inventory & Lessons

… a telegraphic review

- Fermions — Pauli's exclusion principle applies
  - *leptons* | *quarks* — ***copy ?!***
  - Spin-½: $\{(e^-,\nu_e),(u,d)\}$, lightest
    $\{(\mu^-,\nu_\mu),(c,s)\}$, medium
    $\{(\tau^-,\nu_\tau),(t,b)\}$ heaviest
    } "Supstance"

- Bosons — Bose-condensate provides the continuous (static) field
  - Spin-0: Higgs
  - Spin-1: γ, $W^\pm$, Z^0, gluons (8)
  - Spin-2: graviton
  } "Mediators"

- *And… ?*

… That's all, folks!

Elementary Particle Inventory

ELEMENTARY PARTICLES

NOVA

	CONTEXT	MASS	CHARGE	SPIN	STRENGTH	RANGE	OBSERVED?	SPARTICLE
BOSONS (forces)								
GRAVITON	gravity	0	0	2	10^{-38}	infinite	no	gravitino
PHOTON	electromagnetism	0	0	1	10^{-2}	infinite	yes	photino
GLUON	strong force	0	0	1	1	10^{-13}	indirectly	gluino
WEAK GAUGE BOSONS								
W^+	weak force	80,000	1	1	10^{-13}	10^{-16}	yes	W+ wino
W^-	weak force	80,000	-1	1	10^{-13}	10^{-16}	yes	W- wino
Z^o	weak force	91,000	0	1	10^{-13}	10^{-16}	yes	zino
HIGGS BOSON	weak force	>78,000	0	0	[?]	[?]	no	Higgsino
FERMIONS (matter)								
LEPTONS, FAMILY 1:								
ELECTRON	radioactive decay	0.51	-1	1/2	n/a	n/a	yes	selectron
ELECTRON NEUTRINO	atomic structure	0?	0	1/2	n/a	n/a	yes	electron sneutrino
QUARKS, FAMILY 1:								
UP	atomic nuclei	5	2/3	1/2	n/a	n/a	indirectly	up squark
DOWN	atomic nuclei	9	-1/3	1/2	n/a	n/a	indirectly	down squark
LEPTONS, FAMILY 2:								
MUON		106	-1	1/2	n/a	n/a	yes	muon slepton
MUON NEUTRINO		~0	0	1/2	n/a	n/a	yes	muon sneutrino
QUARKS, FAMILY 2:								
CHARM		1,400	2/3	1/2	n/a	n/a	indirectly	charm squark
STRANGE		170	-1/3	1/2	n/a	n/a	indirectly	strange squark
LEPTONS, FAMILY 3:								
TAU		1,784	-1	1/2	n/a	n/a	yes	tau slepton
TAU NEUTRINO		>35	0	1/2	n/a	n/a	yes	tau sneutrino
QUARKS, FAMILY 3:								
TOP		174,000	2/3	1/2	n/a	n/a	indirectly	top squark
BOTTOM		4,400	-1/3	1/2	n/a	n/a	indirectly	bottom squark

http://www.pbs.org/wgbh/nova/elegant/part-flash.html

Elementary Particle Inventory

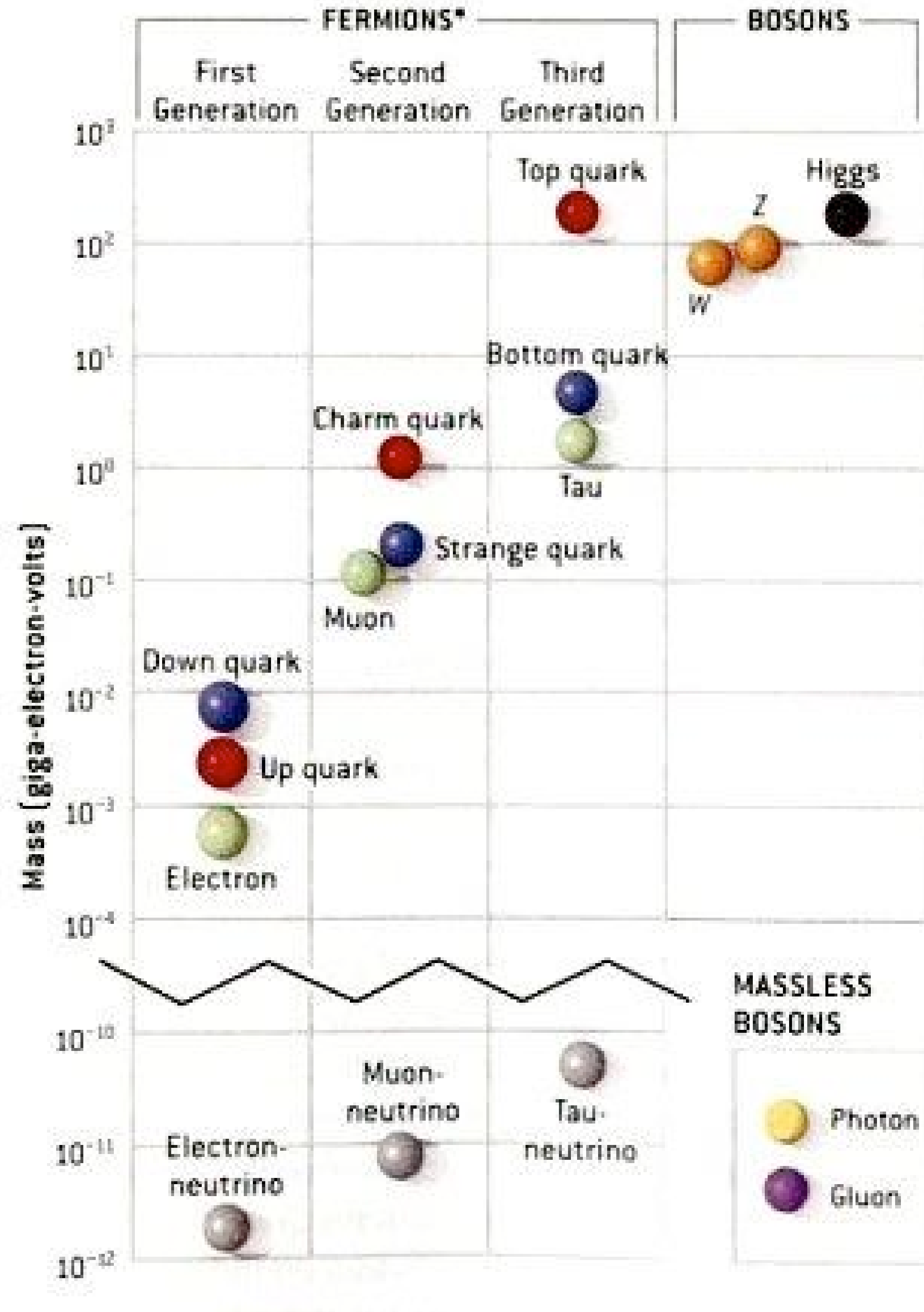
Name / Energy			*Spin*	*Q*	$I_3^{(W)}$
ν_e < 3 eV	ν_μ < 0.19 MeV	ν_τ < 18.2 MeV	±½	0	+½
e .511 MeV	μ 106 MeV	τ 1.78 GeV	±½	–1	–½
u,u,u 1.5–4.5 MeV	c,c,c 1.0–1.4 GeV	t,t,t .17–.18 TeV	±½	+⅔	+½
d,d,d 5.0–8.5 MeV	s,s,s .08–.15 GeV	b,b,b 4.0–4.5 GeV	±½	–⅓	–½

Plus interaction mediators: photon, $W^{\pm}$, Z^0, gluon & graviton.

& Higgs particle.

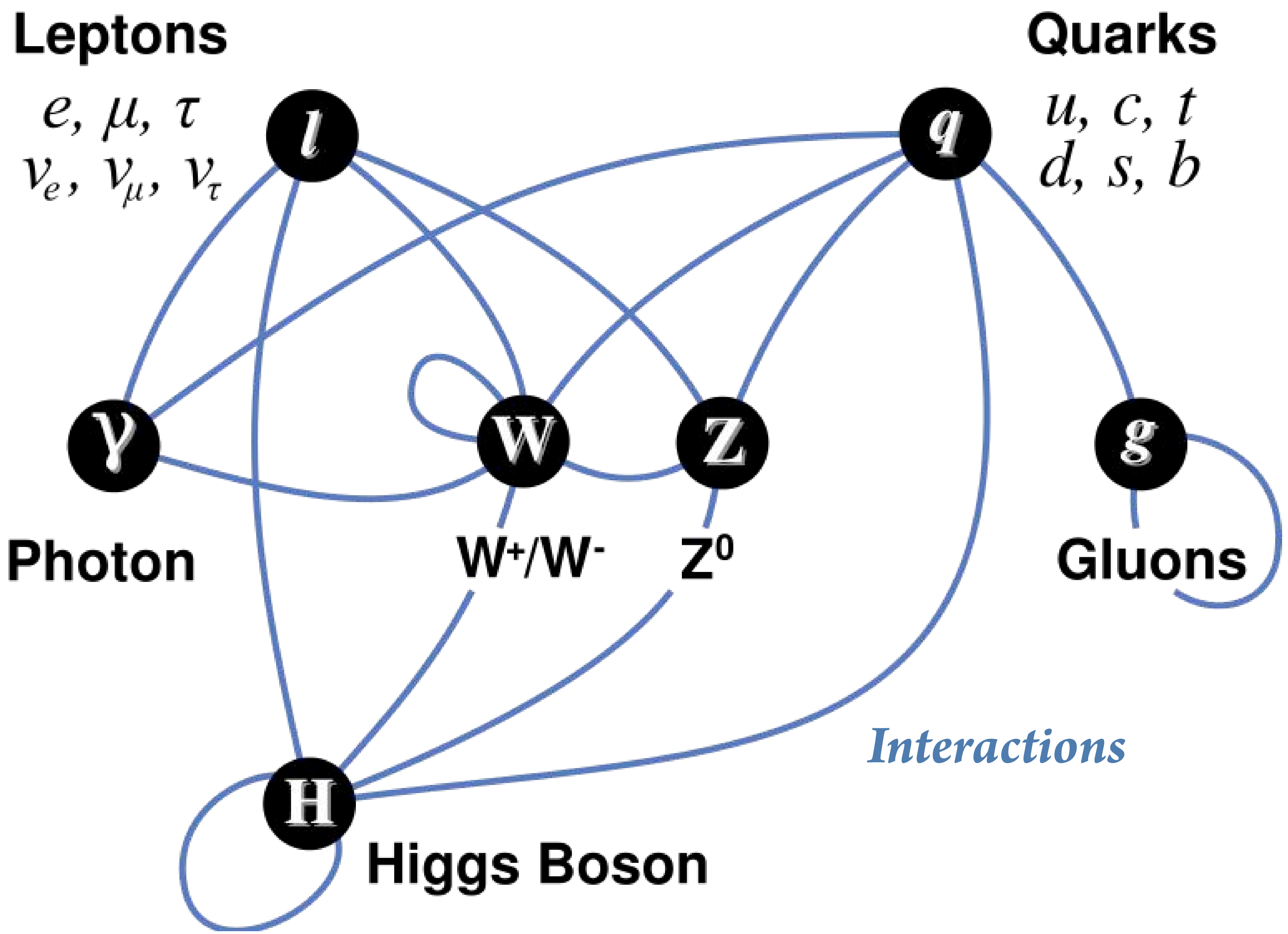
Why 3 ?!

Elementary Particle Inventory



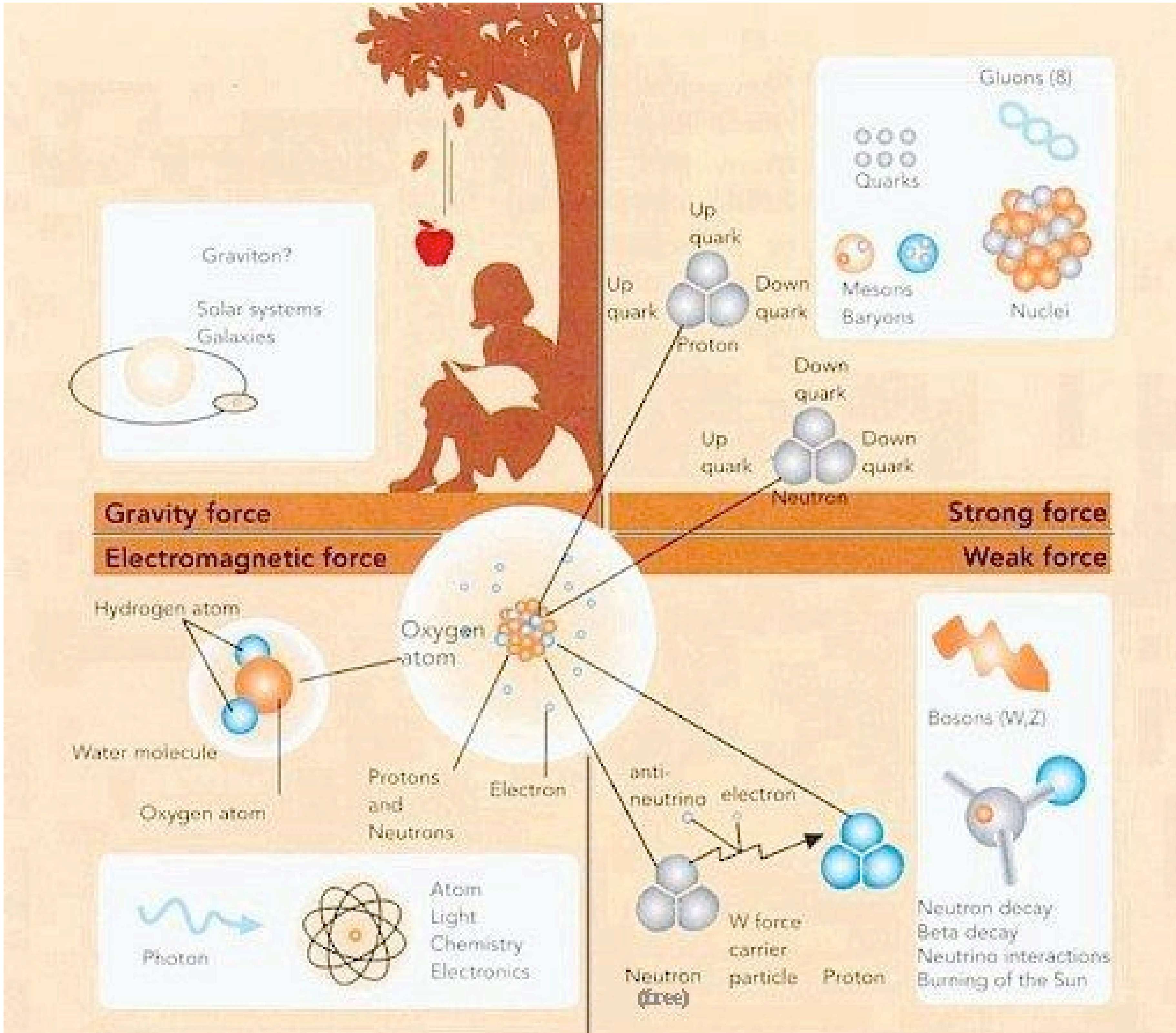
http://universe-review.ca/F15-particle.htm

Elementary Particle Inventory



http://ebiquity.umbc.edu/blogger/wp-content/uploads/2008/07/socparticles1.png

Elementary Particle Inventory



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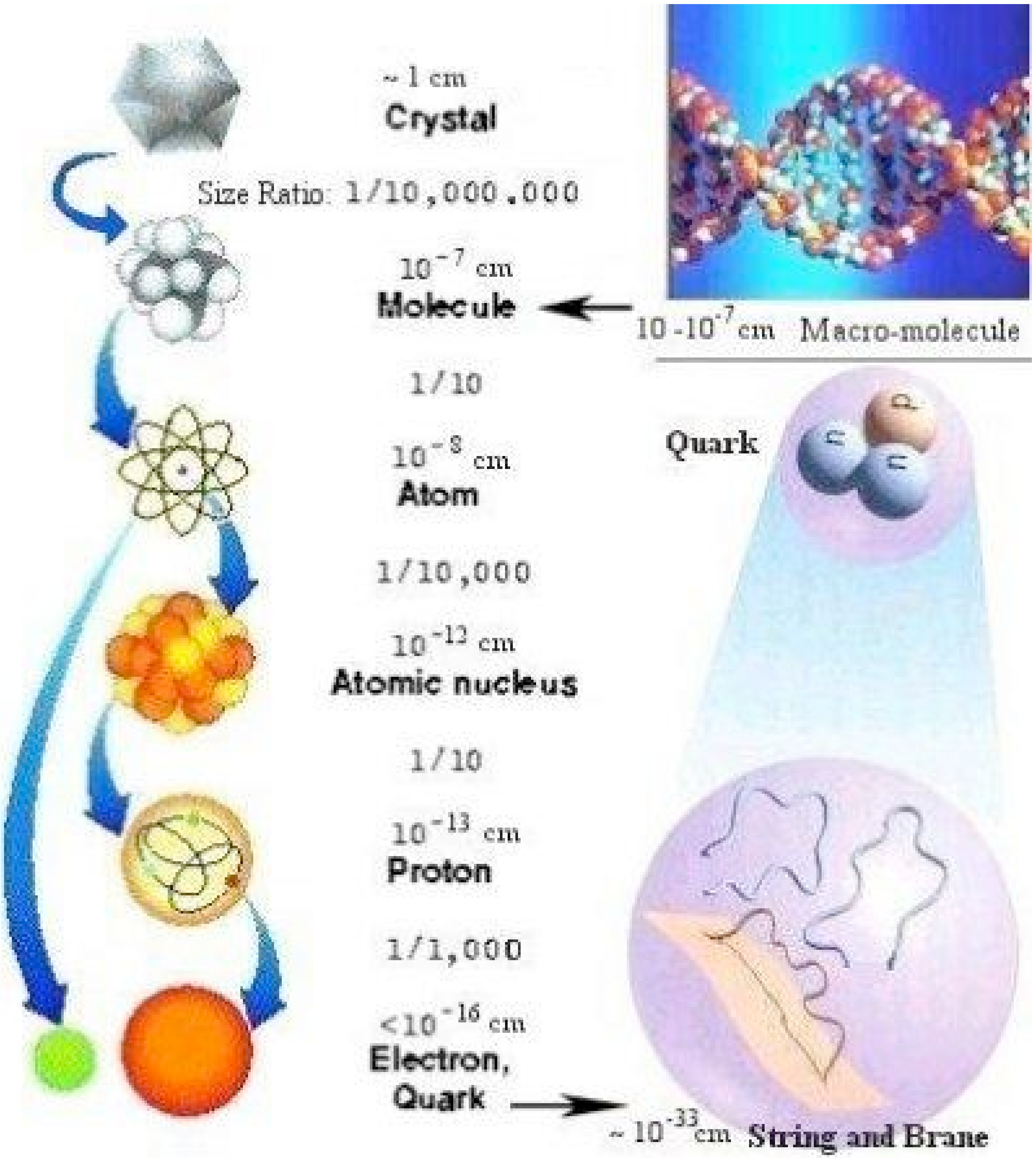
Elementary Particle Inventory



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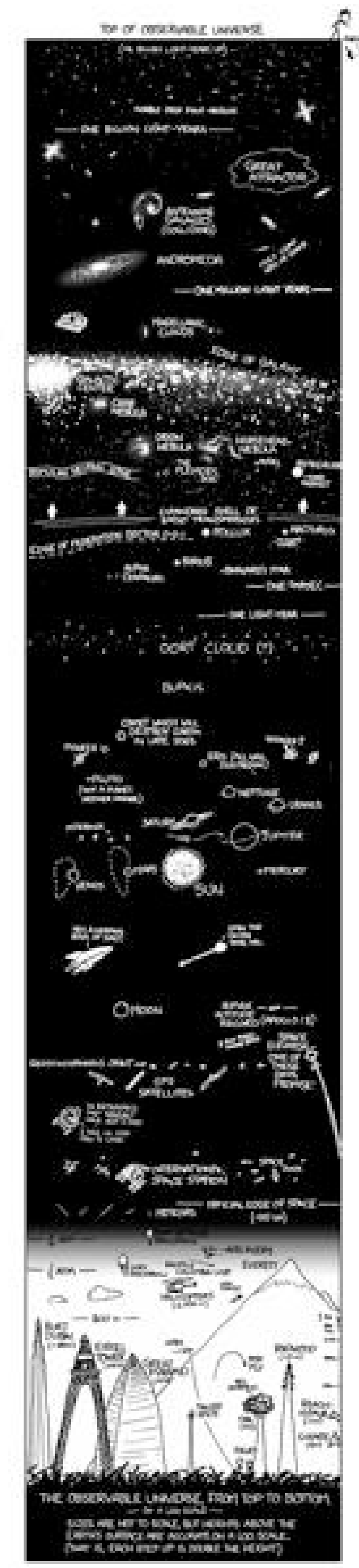

http://xkcd.com/482/

Elementary Particle Inventory

Students—such as you—have, originally "by hand", measured and computed trajectories, curvatures, charges, masses, …

Nowadays, mostly done by computers… ☺

…no longer an opportunity for a nice summer job… ☹

Thanks for staying awake!

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http://homepage.mac.com/thubsch/